
TITLE **VDSL2 should also withstand "PEIN" impulse noise**

PROJECT VDSL2

SOURCE: KPN, TNO[1]

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STATUS For Information & Discussion

ABSTRACT Impulse noise has been widely recognised as an important impairment for VDSL. The REIN and SHINE models do not cover the full range of real-world impulse noise events. Measurements in the Dutch access network highlight the presence of a considerable amount of impulse noise events with lengths between 1 and 10 ms (PEIN). The purpose of this contribution is to share these measurements, create awareness about this type of impulse noise and to progress development work on xDSL protection mechanisms against it.

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1. Introduction

The last couple of years, awareness has been raised about the problem of impulse noise. In particular British Telecom has been active in investigating the problems of repetitive electrical impulse noise (REIN), and in specifying tests to measure the robustness of modem links against this type of noise [1][2][3][4].

It is now commonly accepted that impulse noise has a significant impact on the Quality of Experience of triple play services delivered by xDSL. Impulse noise consists of short bursts of noise that originate from outside the cable. Such impulse noise need not lead to a reduction of the achievable bandwidth, but can lead to the occurrence of short bursts of bit errors and therefore to packet loss on the Ethernet layer. The consequence of this is that impulse noise may not be a big problem for Internet-only services, but that it may severely disturb video services and other triple play services.

Currently, increasing the robustness of xDSL transmission (in particular VDSL2) against impulse noise is an important issue in various standardisation bodies. Mechanisms such as Impulse Noise Protection (INP) are already part of the ADSL2+ and VDSL2 standards. Methods such as Impulse Noise Monitoring (INM) are under study: these methods should aid the operator in selecting the appropriate INP settings for a particular xDSL line. As a novel approach in xDSL, retransmission schemes are considered to be added to the VDSL standards, as an alternative method to combat impulse noise.

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[1] **The work behind this contribution has also been funded by MUSE, a European consortium of vendors, operators and knowledge institutes, cooperating within the 6th framework programme of the European Commission.**

For development work as described above, insight into the characteristics of impulse noise as it occurs in real operational access networks can be very helpful. Therefore, this contribution reports on impulse noise measurements that were performed in KPN's access network. The aim of this contribution is to:

- Increase understanding about the character of impulse noise in an access network.
- To support development work on protection mechanisms against impulse noise.
- To argue that attempts of modem designers to counteract impulse noise should not focus exclusively on REIN or SHINE. Also non-repetitive impulse noise consisting of pulses with lengths between 1 and 10 ms (PEIN) needs to be taken into account when developing methods for impulse noise protection.

2. Measurement setup

In the measurement set-up a current probe is used to detect common mode pulses, close to the CPE modem. For this, the current probe encloses both wires of the wire pair that is carrying the operational ADSL2+ link. The reasons for measuring on the common mode are as follows:

- Measuring the differential mode voltage while the ADSL2+ link is operational makes the detection of impulse noise impossible.
- Simultaneous with the impulse noise events, the CRC error behaviour of the link under test is recorded. This allows to correlate the properties of the impulse noise with the occurring errors[2].
- Replacing the CPE modem by a passive resistor will alter the common mode circuit. Subsequently measuring the differential mode voltage will not give a realistic view of the impulse noise environment.

In the measurement set-up, the current probe is connected to an oscilloscope. The oscilloscope is controlled by the MatLab program "Spike" running on a laptop computer that is connected to the oscilloscope by a GPIB interface. The controlling program automatically provides the oscilloscope with sane settings (see Table 1) and stores measured pulses on the hard disk of the laptop. In this way, pulses can be recorded for prolonged periods of time (typically 24 hour measurements).

Parameter	**Settings 1**	**Settings 2**
Sample Speed	10 MS/s	1 MS/s
Number of samples	50.000	50.000
Total sample length	5 ms	50 ms
Range	Dynamic	Dynamic
Trigger level	Dynamic	Dynamic
Trigger position	25%	25%
Coupling	DC, 50 Ω, LPF: 20 MHz	DC, 50 Ω, LPF: 20 MHz

Table 1: Oscilloscope settings for the measurements. The 'dynamic' values for the parameters are set on the fly by the MatLab program Spike, based on measured background levels and on the interval times between trigger events.

The measurement set-up has a number of identified limitations:

- Finite length of measured samples.
- Clipping of measurement values due to selected range of scope.
- "Black-out" period of ~1.5 s during the storing of a pulse event.
- Under-sampling due to too high LPF (20 MHz) at input of scope.
- Measurements on the common mode need to be re-interpreted as measurements on the differential mode

As a consequence, the recorded pulses are not a fully faithful representation of the real-world impulse noise environment. However, more detailed research and measurements showed that

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[2] This correlation study is outside the scope of the present contribution

many important properties of the impulse noise as it manifests itself on the differential mode can be derived directly from the common mode measurements. This holds in particular for the duration of the impulse noise event, the number of discernible sub-pulses and the spectral content of the pulses[3].

3. Some typical results

Measurements were taken on four different operational ADSL2+ links. The quality of the delivered video services over these lines was known to be unsatisfactory. For reference, measurements were also taken on an operational ADSL2+ line with no known problems. The emphasis of the measurements was to gain insight into the impulse noise environment. No systematic search was undertaken to find the individual sources of the impulse noise events.

As a general observation, all different sort of impulse events could be observed on the line: short/long pulses, single/composite pulses, pulse trains, etc, etc. The graphs below show some typical examples[4] of these categories. Different colours are used to distinguish the sub pulses (see also the next section). More examples can be found in the annex to this contribution.

To increase the understanding about impulse noise further, the following method is useful. The measured pulses can be played back with an ordinary sound card in a PC. To make sure that the signal is audible, the pulses should not be played back at their original sample speed of 10 MHz (or 1MHz) but at a rate of 40 kHz. In this way, the human ear can be used in the analysis of the impulse noise. This method proved to be very powerful in studying both the temporal as well as the spectral properties of the impulse noise events. Among others, it helped to demonstrate the high degree of similarity between the common mode and the differential mode measurement of the same impulse event.

Audio versions of some of the measurements are available with the author on request.

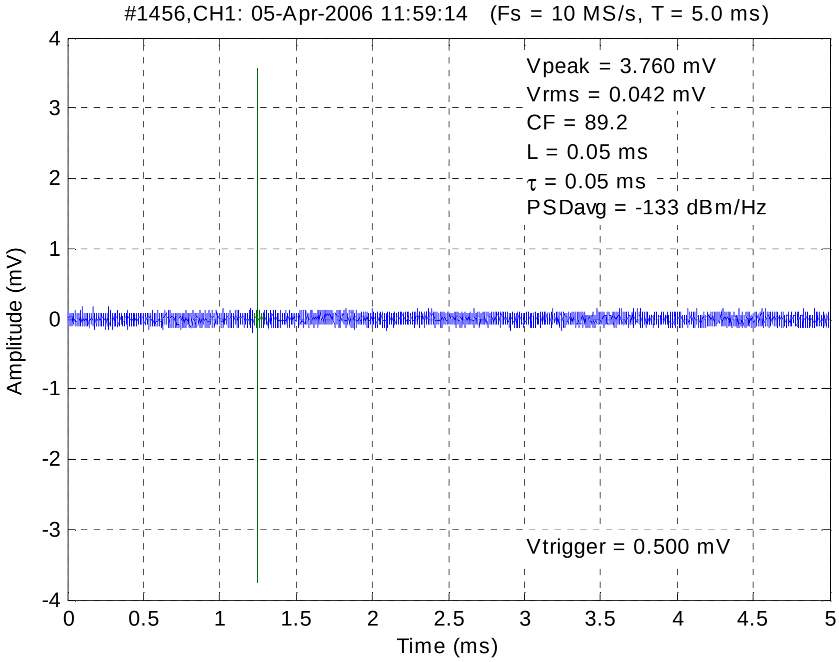

Figure 1: Example of an impulse noise event consisting of a single pulse. See Table 2 for the definition of the various characteristic properties printed in the plot.

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[3] In contrast, information on the absolute magnitude of the impulse noise event on the differential mode is difficult to deduce from the common mode measurement.

[4] The magnitude of these impulse noise events (as expressed e.g. in terms of the quantity PSD_{avg}) are related to the *common mode current* that was measured; it is difficult to relate this magnitude to the differential mode power of these pulses.

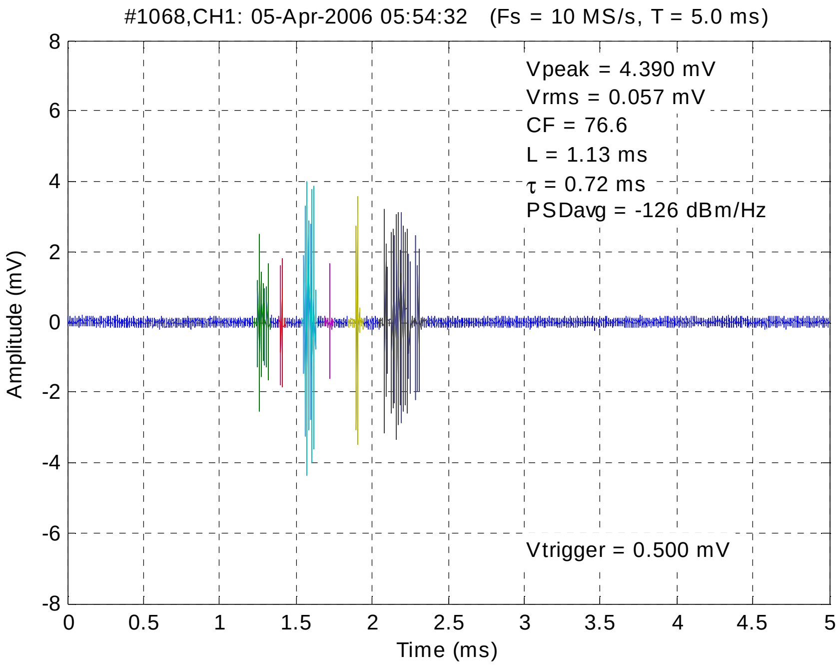

Figure 2: Example of a composite impulse noise event. A number of sub pulses can be distinguished.

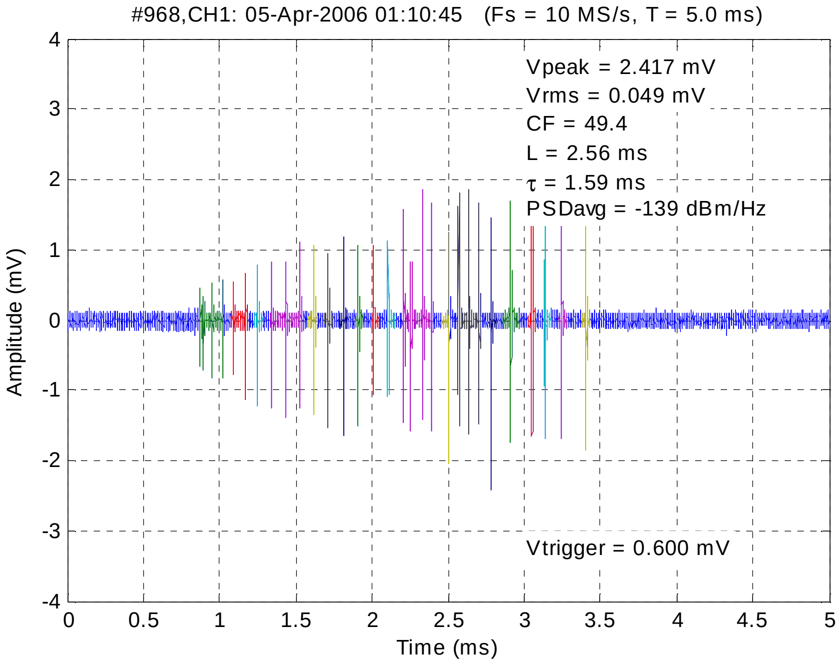

Figure 3: Another example of a composite impulse noise event. This noise event consists of a long pulse train of short sub pulses.

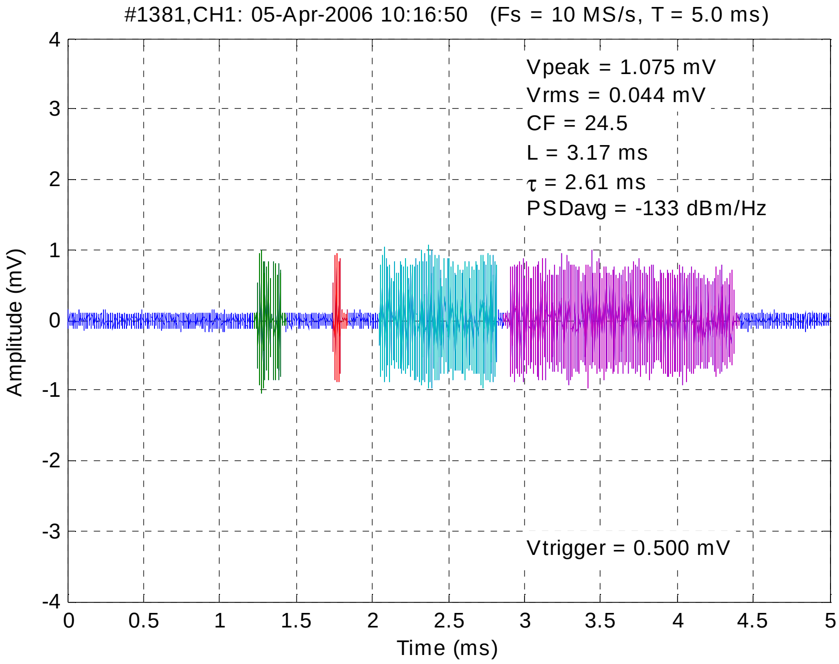

Figure 4: Another example of a composite impulse noise event. Compared to the previous plot, the sub pulses in the current plot are much longer.

4. Characteristic properties of impulse noise

In this section the statistical distribution of certain characteristic quantities of the measured impulse noise events are studied. Typical characteristic quantities are the peak voltage, the length and the inter-arrival times of impulse noise events. These properties have for instance been studied for the British and the German telephone network [5][6].

A 24 hour measurement on a line resulted in typically between 1000 and 2000 recorded pulses[5]. The measured pulses showed a large spread in terms of their peak level, pulse length, spectral characteristics, number of discernible sub pulses, etc.

4.1. Definition of characteristic properties

The automatic determination of the characteristic properties for the pulses requires some care. The most important properties discussed in this contribution (see Table 2) start with the identification of the sub pulses in an impulse noise event. For this, the following procedure is used:

- First, the pulse is subdivided in segments of 512 samples. With a total sample length of 50000, this leads to roughly 100 segments.
- Next, for each of these segments the peak voltage and root-mean-square voltage are calculated. By dividing these numbers by $V_{rms,\ bg}$ (the background RMS voltage), dimensionless numbers are obtained that characterise the pulse.
- Finally, sub pulses can be identified by requiring that these numbers are above a certain threshold value .

The identification of sub pulses is somewhat arbitrary. In particular, it is affected by the chosen threshold values. Nevertheless, by choosing these values carefully, it is possible to have the automated identification algorithm result in almost the same identification of the sub pulses that a human would make (which of course still implies a certain level of arbitrariness). Referring back to the previous section, the “isolated impulse event” of Figure 1 only has one sub pulse, whereas the “composite impulse event” of Figure 4 has four sub pulses.

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[5] This number is more or less independent from the link under study, because of the dynamic way the trigger level of the scope is set.

Characteristic quantity	**Description**
Vrms, bg	The root-mean-square value of the first[6] 20% of the recorded pulse, i.e. before the actual trigger event occurred. This value is a measure of the background signal.
Vpeak	The maximum of the absolute value of the measured voltage.
CF	The crest factor: Vpeak / Vrms, bg. This is a measure for how strong the impulse noise event is, in relation to the background signal.
nr	The number of identified sub pulses.
Length	Time between the start of the first sub pulse and the end of the last sub pulse.
τ	Sum of the duration of all the identified sub pulses. This “demolition time” can be considered to be the effective time during which the pulse event could actually cause harm to the xDSL signal.

Table 2: Some characteristic quantities for an impulse noise event.

4.2. Distribution of the pulse length

Figure 5 shows the cumulative distribution of the pulse length, based on the four 24h measurements that used a sample speed of 10 MS/s, i.e. a total sample length of 5 ms. These curves all show that the bulk of the pulse events are short, but that there is a small but non-negligible set of longer pulses. For comparison, the red vertical lines give some common choices for the INP parameter. Roughly speaking, the fraction of pulses that are longer than the selected INP value (and that are sufficiently strong) is expected to lead to transmission errors.

Three of the curves are similar. The ‘Amsterdam’ curve exhibits a relatively large fraction of long pulses. On inspection of the individual pulse events, it turned out that this was caused by the presence of some repetitive noise (REIN) on the line. On the other lines, no REIN could be observed or it was much smaller in magnitude than the non-repetitive impulse noise.

The curve ‘TVlab’ corresponds to an ADSL2+ line at the TNO facilities. This line is also part of the operational network, but in contrast with the other four lines, it is not a line with known problems. This is nicely reflected by the fact that few long pulses were measured on this line.

Figure 5 shows that the length of the pulse events can be of the order of the measurement window[7] of 5 ms. This raises the question whether even longer pulse events (or pulse trains) occur in practice. To measure this, the sample speed of the oscilloscope was lowered to 1 MHz, increasing the measurement window to 50 ms.

Figure 6 shows the same curves as Figure 5, but now two extra curves corresponding to 50 ms measure time are added. The ‘Amsterdam’ curve (yellow) is again biased because of the occurrence of REIN on the line, but the ‘Sliedrecht’ curve (black) demonstrates that even in the absence of REIN, pulse events can last up to tens of milliseconds. It is expected that impulse events that are in the tail of the pulse length distribution will be difficult to counteract with INP.

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[6] Actually, the root-mean-square voltage is calculated for the first 20% and for the last 20% of the signal. The minimum of these two values is used.

[7] After measuring a 5 ms window, the measurement set-up is transfering the data to the laptop. This results in a ‘black-out’ window of approximately 1 to 2 seconds during which no measurements are made.

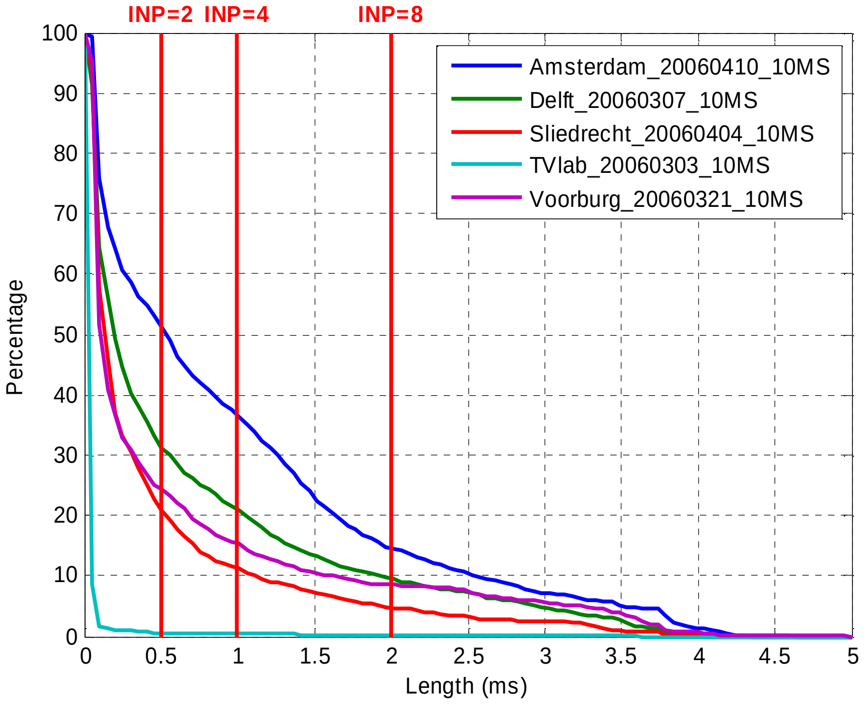

Figure 5: Cumulative distribution of the pulse lengths for the 5ms measurements.

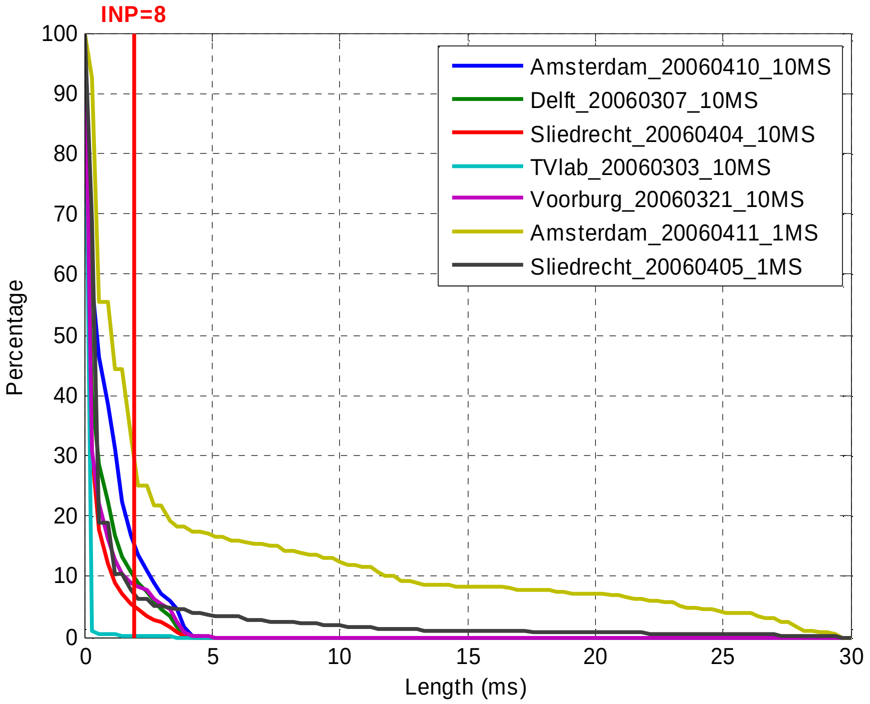

Figure 6: Cumulative distribution of the pulse lengths for both the 5ms and 50ms measurements.

4.3. Distribution of the effective "demolition" time

Figure 7 shows the distribution of τ, which is defined as the sum of the duration of all the identified sub pulses. This quantity can be considered as the effective "demolition" time: during the time τ, the pulse event can cause harm to the ADSL transmission.

As in the case of total pulse length, one might expect that the fraction of pulses with τ larger than the INP value could lead to transmission errors. In this way, a first guess of the quantitative benefits of increasing the INP value can be obtained. The plot suggest that increasing the INP from e.g. 2 to 4 would reduce the fraction of pulses that can cause transmission errors from 10% to 5%. This is of course just a crude estimate: also the strength of the pulse and the number of sub pulses will determine how many DMT symbols will be damaged.

Note the strong similarity between the curves 'Delft', 'Sliedrecht' and 'Voorburg'.

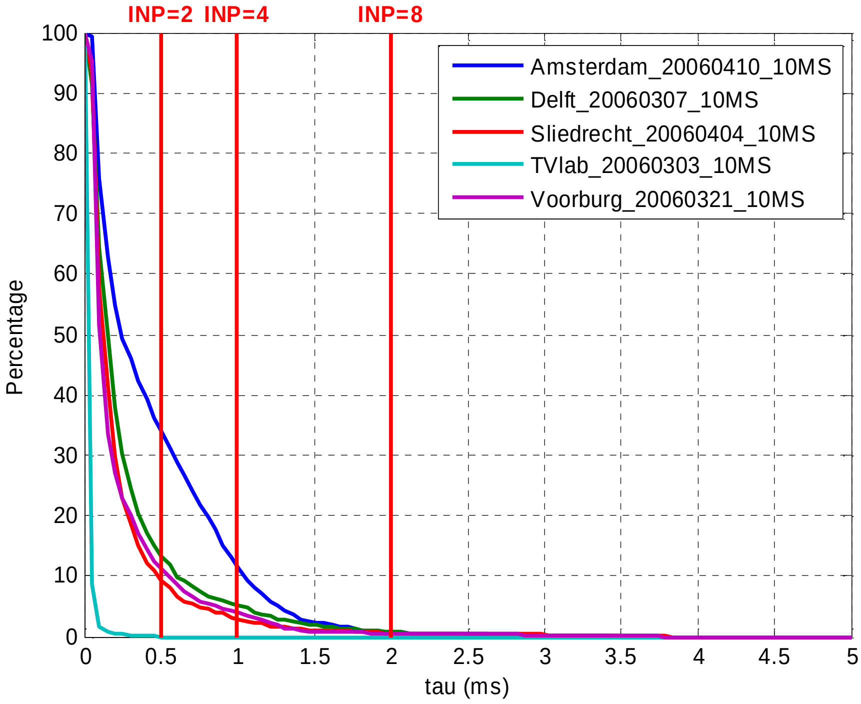

Figure 7: Cumulative distribution of t , the sum of the duration of all the identified sub pulses (see Table 2).

4.4. Distribution of the Crest Factor

Figure 8 shows the distribution of the crest factor (CF) of the pulses. The almost linear behaviour of the cumulative distribution function in the range 40 < CF < 80 shows that pulses in this range are all almost equally probable. The distribution seems to be limited to Crest Factor < 100, but this is due to the limited dynamical range of the measurement set-up. The reference measurement on the line in TNO's TVlab shows that pulse events with a crest factor higher than 20 are already quite unlikely for this clean line.

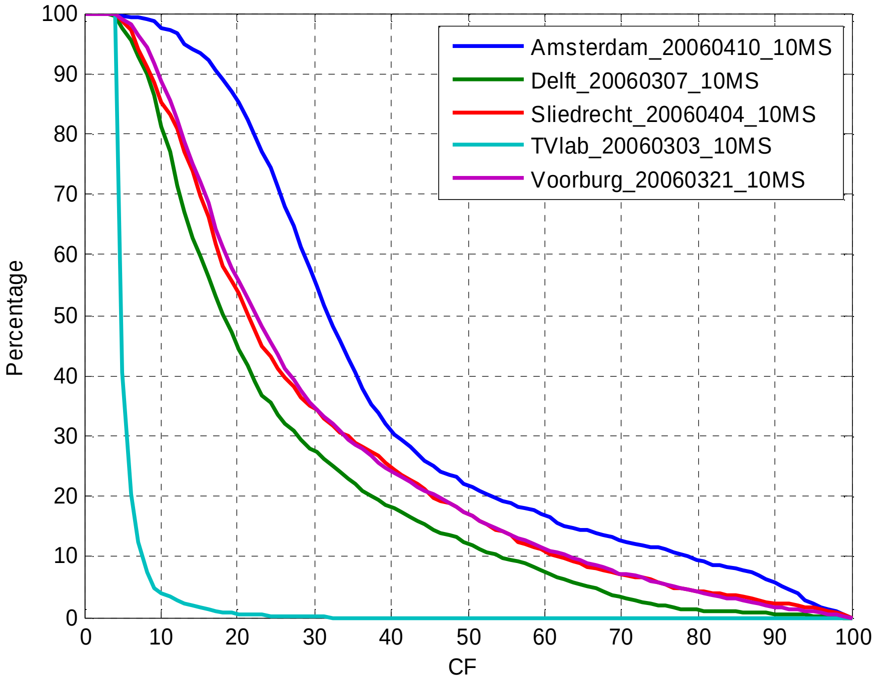

Figure 8: Cumulative distribution of the Crest Factor of the pulses. Due to the way of recording the pulses, all measured pulses have a Crest Factor of at least 5 and of maximally approximately 100.

4.5. Distribution of the number of sub pulses

As explained earlier, the number of identified sub pulses is somewhat dependent on the precise criteria being used by the automated detection algorithm. That having said, Figure 9 illustrates the distribution between isolated impulse events and composite impulse events. As a rule of thumb, roughly half of the measured events consist of isolated impulse events; the other half consists of composite impulse events such as e.g. pulse trains.

Note that the measurement in TNO's TVlab is an exception to this rule of thumb. On this clean line the adaptive measurement method recorded mostly low level impulse events, for which the subsequent sub pulse identification algorithm could not detect the presence of any sub pulses.

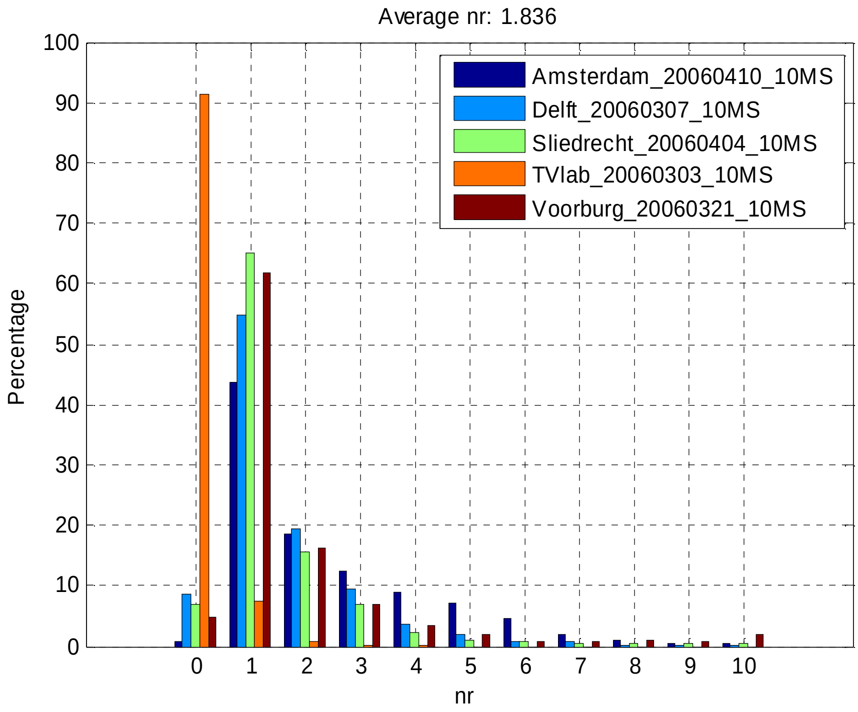

Figure 9: Distribution of the number of identified sub pulses, within the measurement time of 5 ms.

5. Prolonged Electrical Impulse Noise (PEIN)

In standardisation much attention has been given to REIN: repetitive noise consisting of short bursts (shorter than 1 ms) of noise. In addition, SHINE has been defined as individual impulse noise events with lengths larger than 10 ms. Although robustness against REIN and SHINE is indeed important, it should not be the exclusive focus of attempts to counteract impulse noise.

The measurements in the Dutch access network suggest that the majority of impulse noise events on problematic ADSL2+ lines in the Netherlands is non-repetitive in nature. In fact, individual impulse noise events with length between 1 ms and 10 ms are suspected to cause the most impulse noise related problems for the Dutch access network, because:

- a considerable fraction (10% to 20 %, see Figure 5) of the measured impulse noise events falls in this category,
- these impulse noise events are not effectively counteracted by the commonly used INP values of two or four.

For this type of impulse noise we introduce the acronym ‘PEIN’: Prolonged Electrical Impulse Noise. PEIN is defined to consist of all non-repetitive impulse noise events that have a duration between 1 ms and 10 ms. Table 3 shows that PEIN is complementary to REIN and SHINE. To counteract PEIN, it is expected that INP values larger than four, or other mechanisms of impulse noise protection are required. In designing new (or optimising existing) impulse noise protection methods, the emphasis should not be exclusively on relatively short pulses (shorter than 1 ms), or on REIN and SHINE, but also on PEIN.

It is left for further study whether a PEIN test needs to be standardised.

Impulse Noise	Typical Burst length	Repetitive?	Desired modem behaviour
REIN	< 1 ms	Yes	No bit errors
PEIN	1 – 10 ms	No	No bit errors
SHINE	> 10 ms	No	No sync loss[8]

Table 3: Differences between various forms of impulse noise. PEIN fills the gap between the already defined REIN and SHINE impulse noise.

6. Using the measured pulses for testing

One of the original aims of the Dutch measurement campaign was to develop a method for "representative" impulse noise testing in the lab. This proved to be a difficult task, due to the wide range of different pulses observed in the field and the limited number of measurement locations. Moreover, it was difficult to establish the correct distribution of the differential mode magnitude of the impulse noise events from the common mode measurements. In general, it is challenging to capture a broad range of observed impulse noise phenomena in a simple (synthetic) description that aims to be a faithful representation of the operational reality.

In order to make progress in specifying test conditions for the lab environment, it was decided to port the measured impulse noise events directly to the lab. The idea is to mimick the real-world impulse noise situation as close as possible by playing back in the lab the samples that were recorded on operational lines in the field. The samples are played back by an arbitrary waveform generator (AWG) card in a PC at the same sampling speed with which they were recorded. The impulse noise injection will be done directly on the differential mode of the link under test, in order to have maximum control over the disturbing impulse. The measured common-mode pulses were scaled by a fixed value that was considered appropriate for injection into the differential mode.

The typical way to use a set of these impulse noise events is by playing them back with approximately 1 second interval in between the pulses. The total number of CRC error events reported by the modem is then a measure of the susceptibility of the line to impulse noise. In this way, the effectiveness of impulse noise protection schemes can be studied:

- By changing the settings of the xDSL line (such as the INP and the delay), the sensitivity of the line to impulse noise should be changed.
- By comparing two different CPE modems using the same settings, differences in modem quality can be demonstrated.

Furthermore, by reading out the CRC counter in the modem after each injected impulse, it can be precisely established which disturbances lead to errors. This can provide more insight into what aspects of a pulse lead to problems for a certain xDSL link.

For this pragmatic definition of an impulse noise test, a handpicked selection of 80 impulse noise events was made. Measurements were used from all four locations, and from measurements both at 10MS/s sample speed and at 1 MS/s sample speed. Although the emphasis was on pulses that are likely to cause problems for an xDSL transceiver, an attempt was made to have all sorts of pulses present in this set: strong, weak, long, short, etc. The plots in the annex provide an impression about the temporal characteristics of these 80 pulses, that have been called "The Dutch Reference Set of Impulse Noise". The purpose adding these plots to this contribution is to convey the large variety of real-world impulse noise events.

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[8] Because of the length of a SHINE burst, it is unrealistic to expect the modem to be able to survive such a noise event without bit errors. Therefore, the main question for SHINE events is whether the modem loses synchronisation or not.

7. Conclusions & Recommendations

Extensive information on the Dutch impulse noise environment was obtained:

- A large variety of impulse noise phenomena can be observed in the Dutch access network: weak, strong, short, long, etc. Both single, isolated pulses exist, as well as prolonged composite pulse events such as pulse trains.
- Some REIN is observed in the Dutch network, but this does not seem to be the dominant form of impulse noise.
- The impulse noise class PEIN has been defined as non-repetitive impulse noise events that have a duration between 1 ms and 10 ms.
- In designing new (or optimising existing) impulse noise protection methods, the emphasis should not be exclusively on relatively short pulses (shorter than 1 ms) or on REIN and SHINE, but also on Prolonged Electrical Impulse Noise (PEIN).

8. References

[1] 042t23, "*Improved Impulse Noise Models for xDSL Testing"*, ETSI TM6 contribution, Gent, June 2004

[2] 043t09, *"Repetitive Electrical Impulse Noise (REIN) Testing for xDSL*", ETSI TM6 contribution, Zurich, August 2004

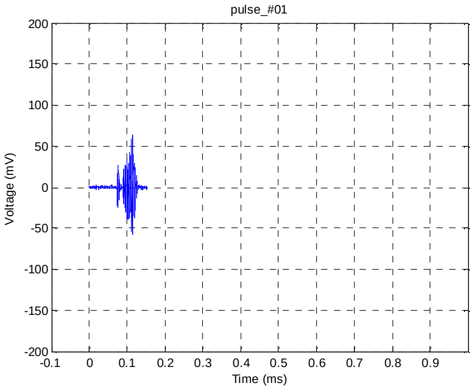
[3] 044t09, *"REIN Test Methodology*", ETSI TM6 contribution, Sophia Antipolis, Nov 2004

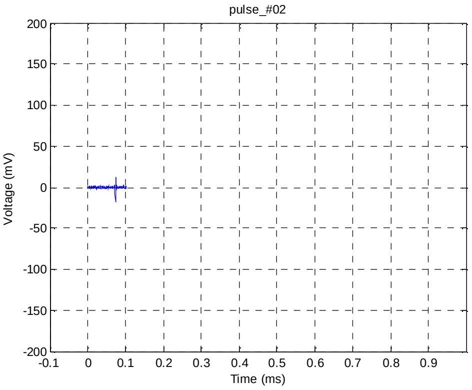
[4] 044t11, *"REIN – Why use AWGN bursts in REIN testing ?"*, ETSI TM6 contribution, Sophia Antipolis, Nov 2004

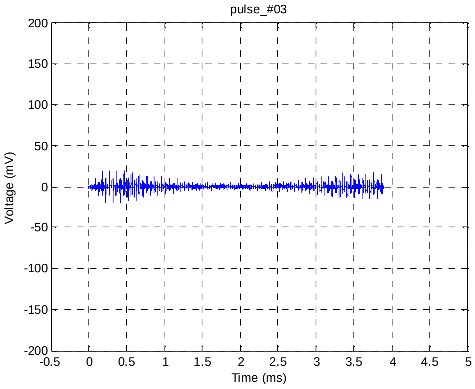
[5] Henkel, Kessler, *"A wideband impulsive noise survey in the German telephone network; Statistical description and modeling",* AEU, vol.48, no.6, pp.277-288, Nov/Dec 1995.

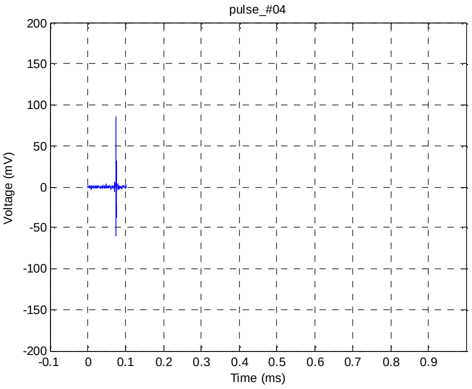
[6] Mann, McLaughlin, Henkel, Kirby, Kessler, *"Impulse generation with appropriate amplitude, length, inter-arrival, and spectral characteristics",* IEEE J. Select. Areas Commun., vol.20, no.5, pp. 901-912, June 2002.

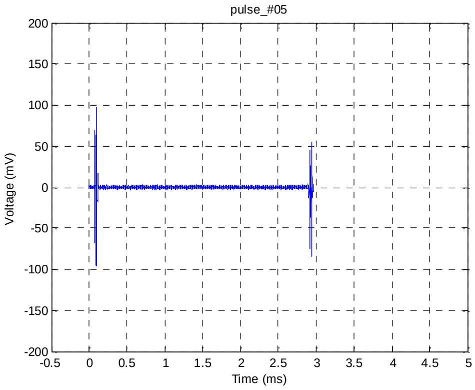
Annex: Dutch Reference Set of Impulse Noise

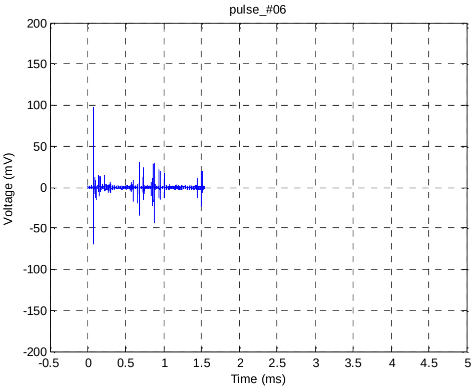


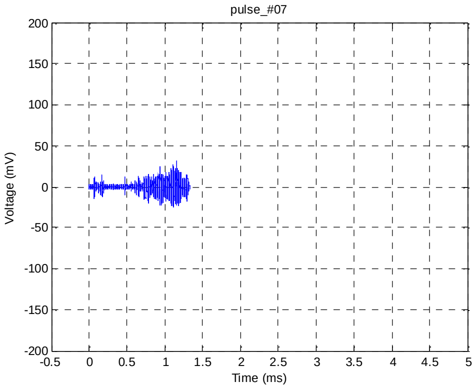


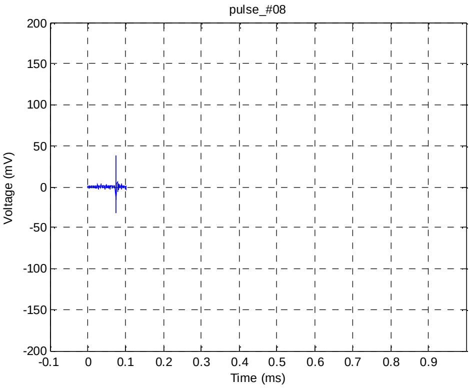


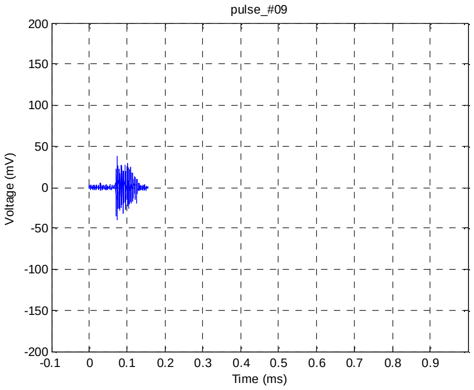








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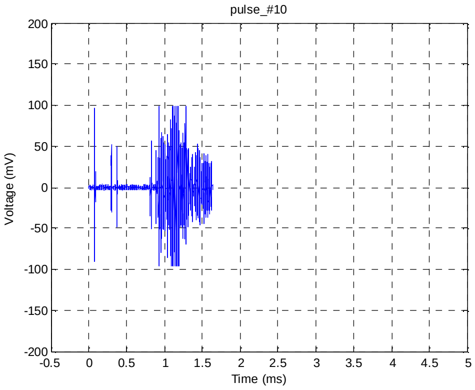
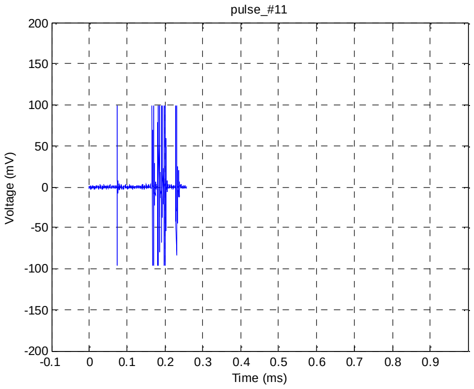
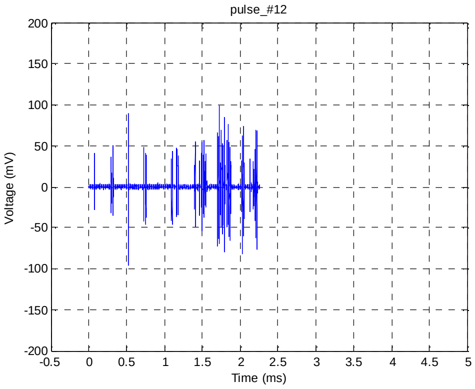
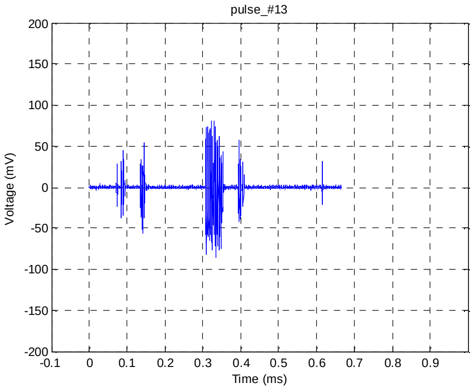
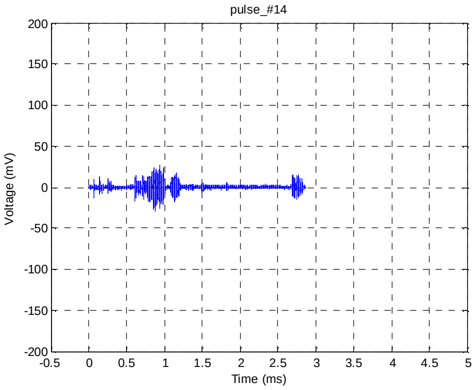
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

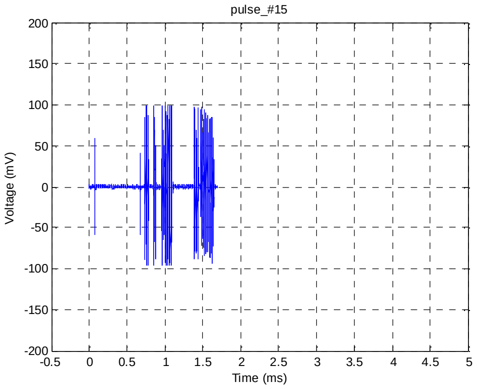

pulse_#10
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

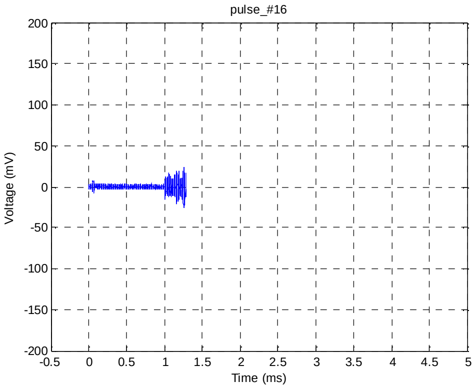

pulse_#11
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

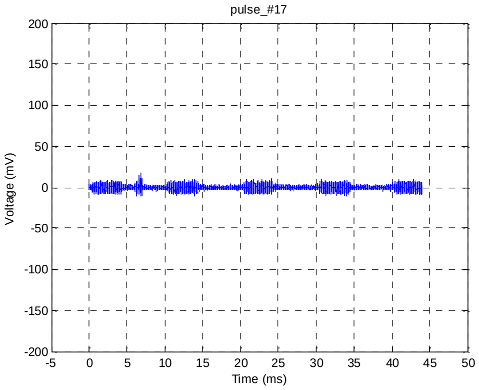

pulse_#12
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

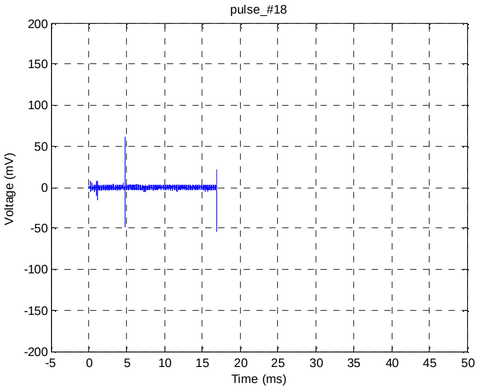

pulse_#13
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

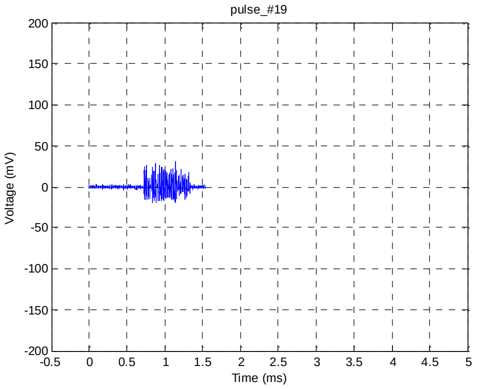

pulse_#14
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

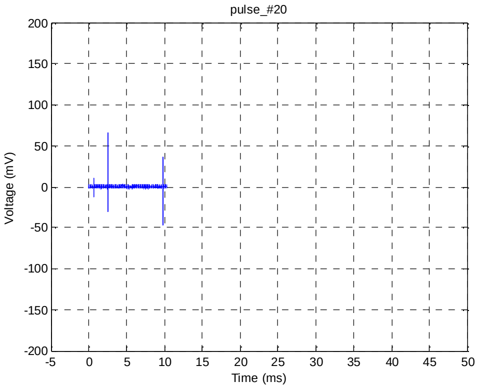

pulse_#15
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

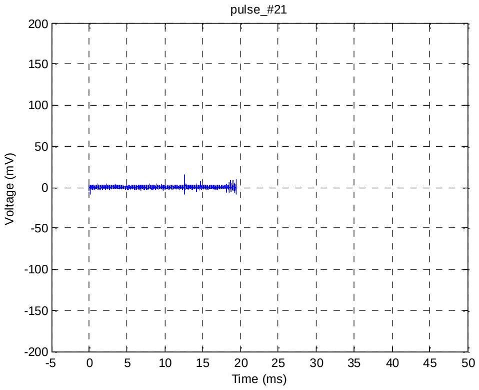

pulse_#16
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

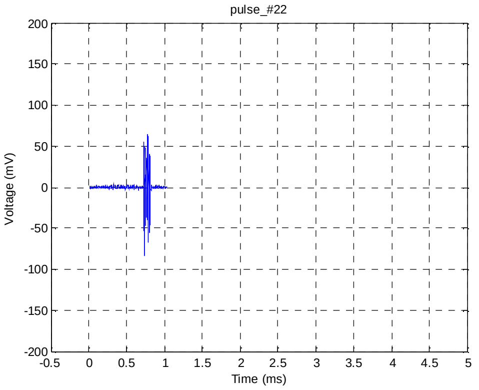

pulse_#17
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-5 0 5 10 15 20 25 30 35 40 45 50
Time (ms)

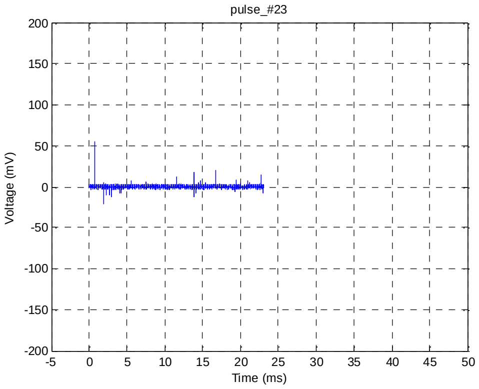

pulse_#18
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-5 0 5 10 15 20 25 30 35 40 45 50
Time (ms)

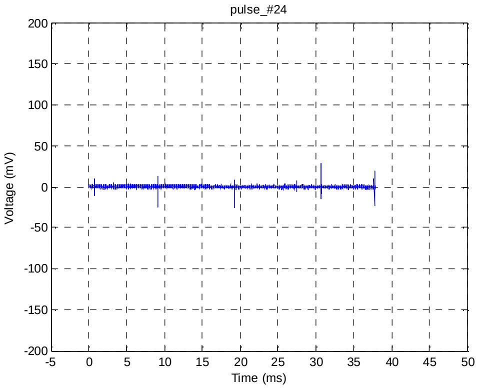

pulse_#19
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
Time (ms)

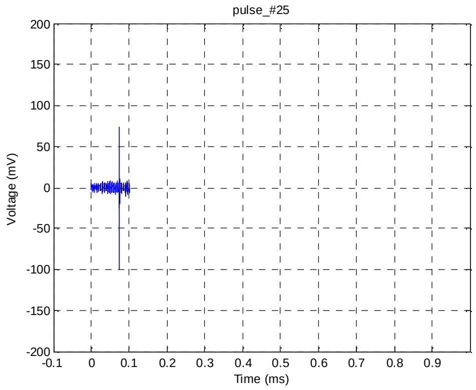

pulse_#20
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-5 0 5 10 15 20 25 30 35 40 45 50
Time (ms)

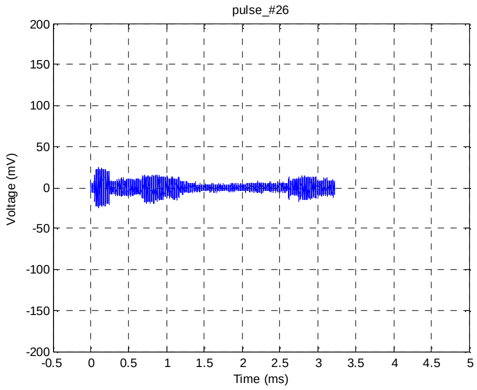

pulse_#21
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-5 0 5 10 15 20 25 30 35 40 45 50
Time (ms)

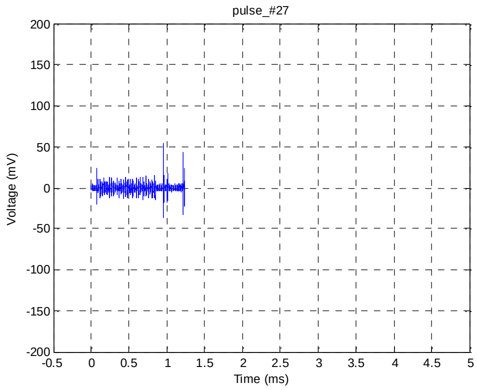

pulse_#22
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
Time (ms)

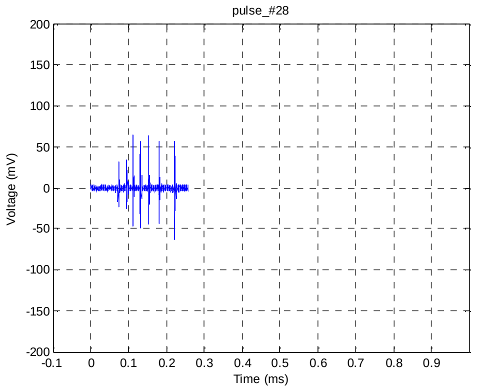

pulse_#23
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-5 0 5 10 15 20 25 30 35 40 45 50
Time (ms)

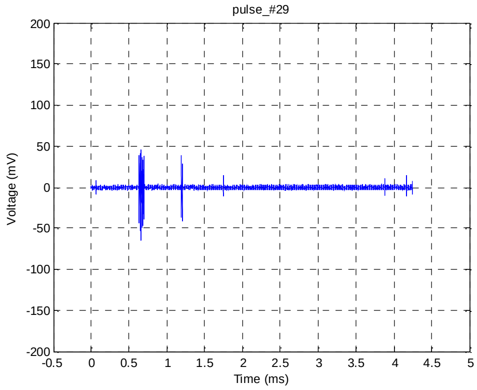

pulse_#24
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-5 0 5 10 15 20 25 30 35 40 45 50
Time (ms)

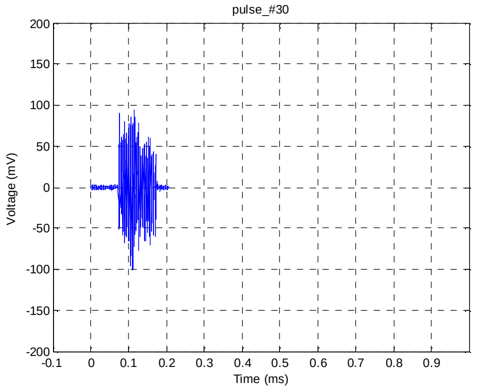

pulse_#25
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

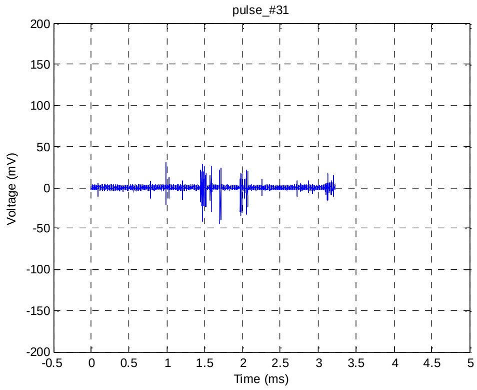

pulse_#26
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

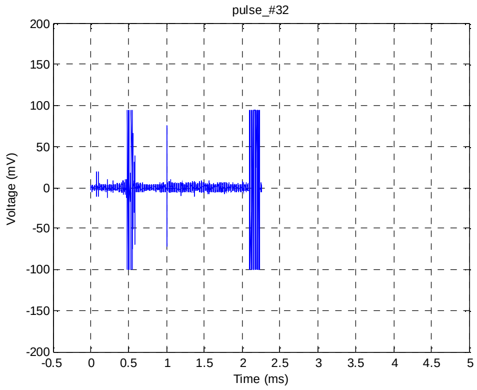

pulse_#27
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

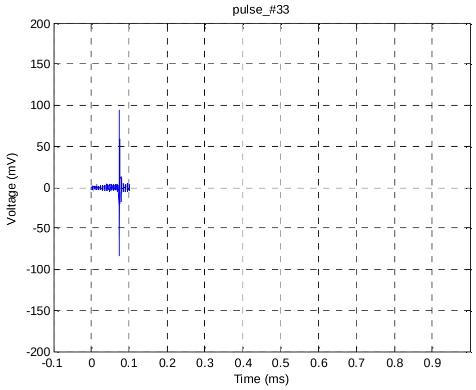

pulse_#28
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

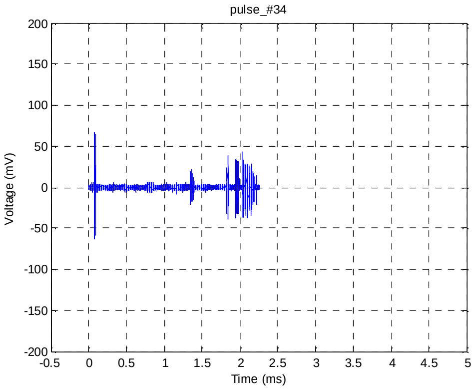

pulse_#29
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

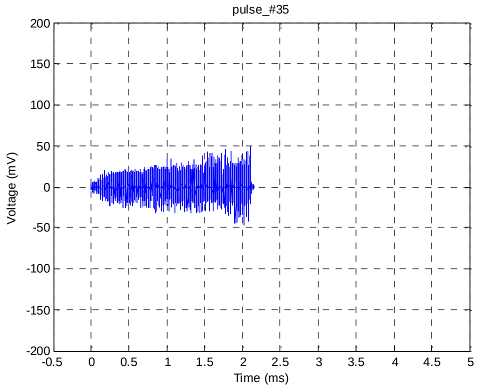

pulse_#30
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

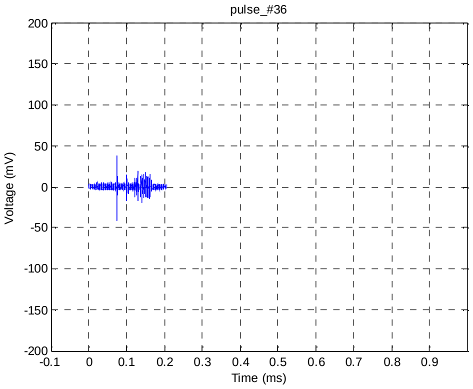

pulse_#31
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

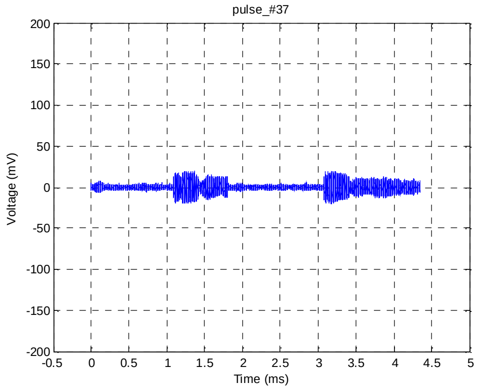

pulse_#32
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

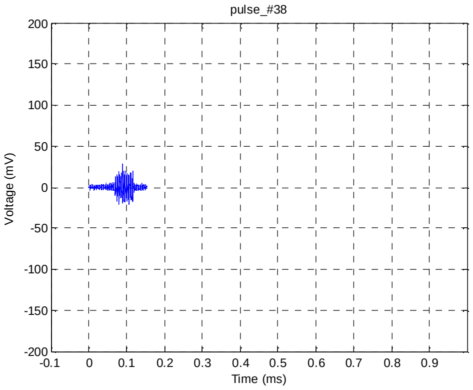

pulse_#33
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

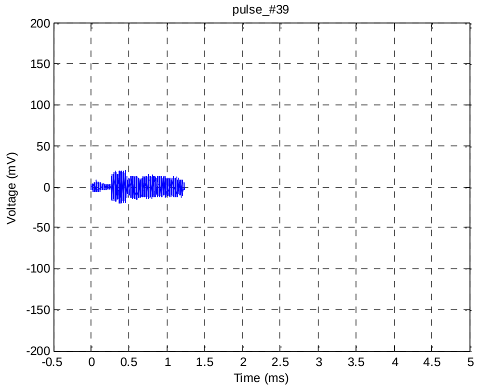

pulse_#34
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

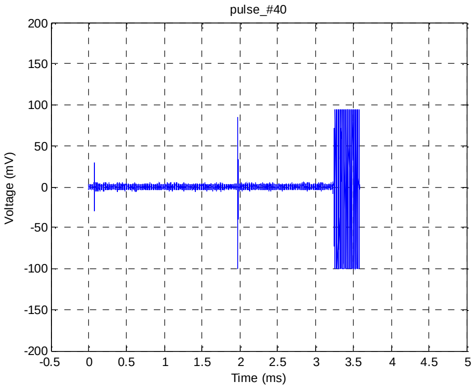

pulse_#35
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

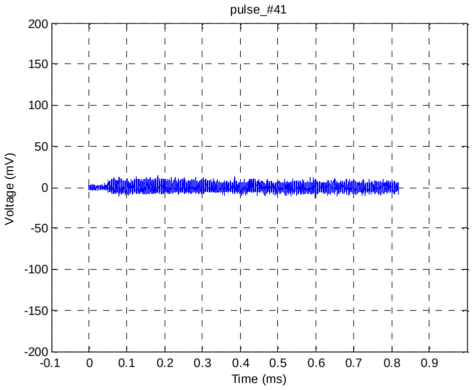

pulse_#36
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

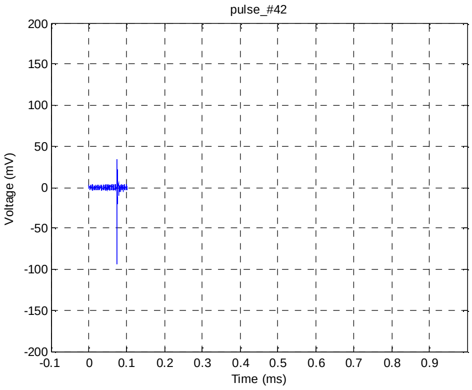

pulse_#37
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

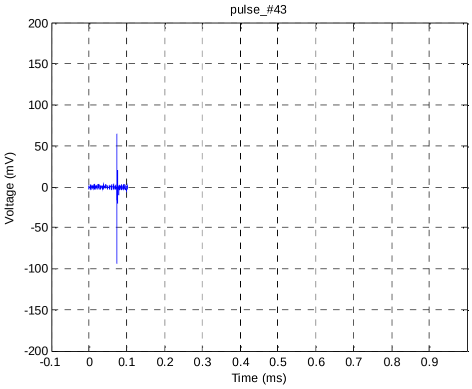

pulse_#38
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

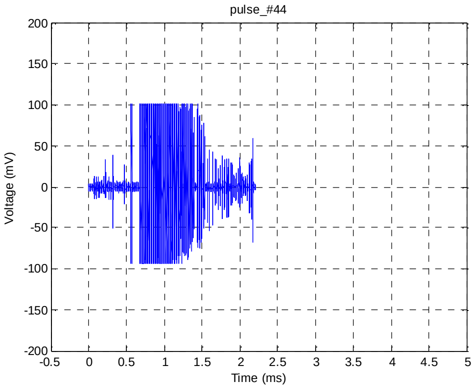

pulse_#39
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

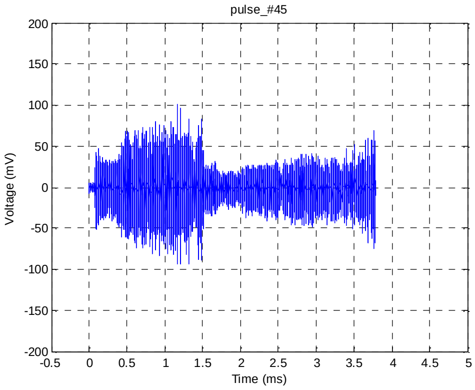

pulse_#40
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

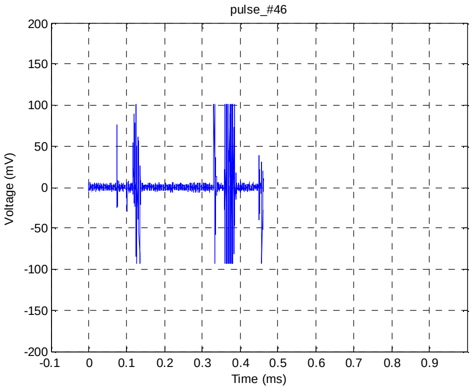

pulse_#41
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

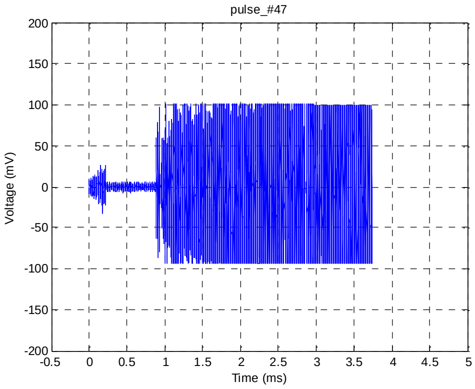

pulse_#42
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

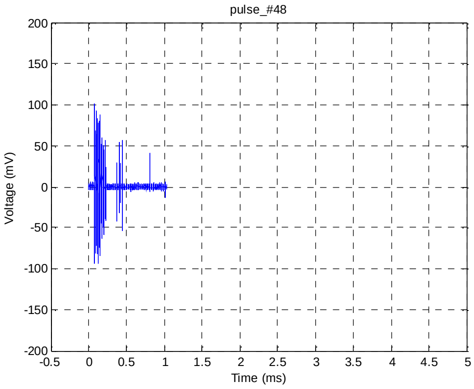

pulse_#43
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

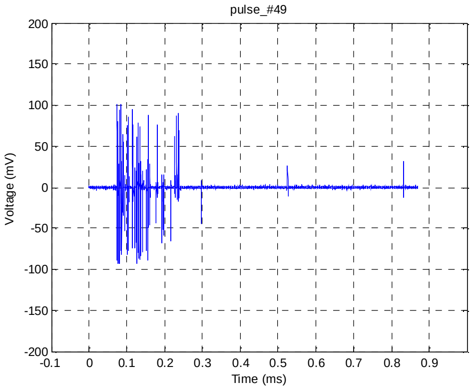

pulse_#44
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

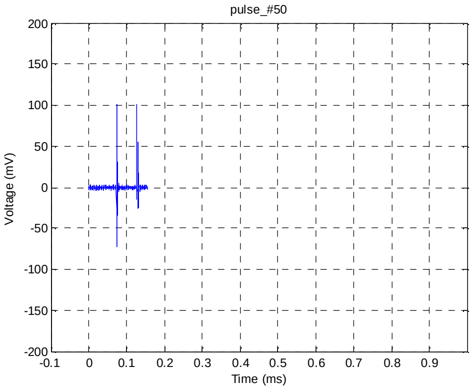

pulse_#45
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

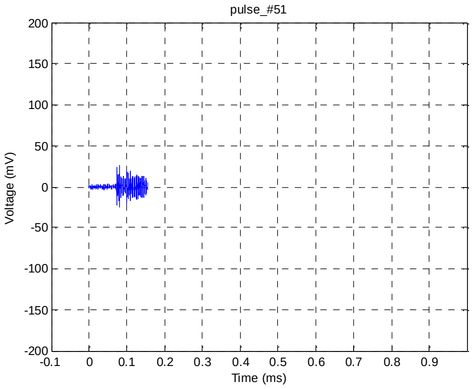

pulse_#46
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (ms)

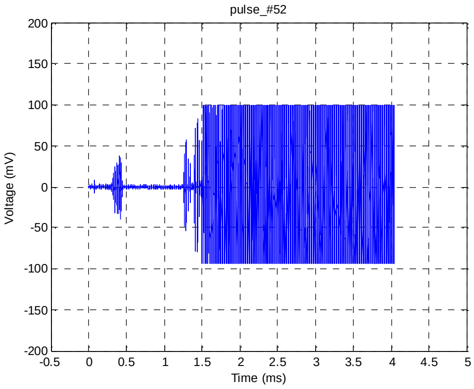

pulse_#47
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

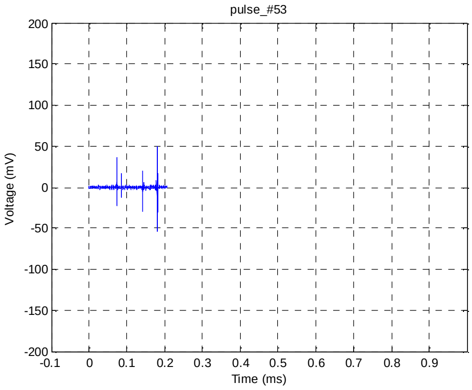

pulse_#48
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

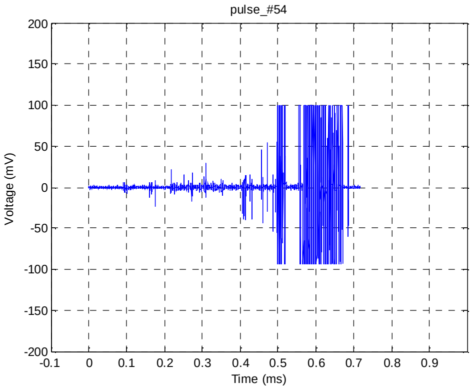

pulse_#49
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
Time (ms)

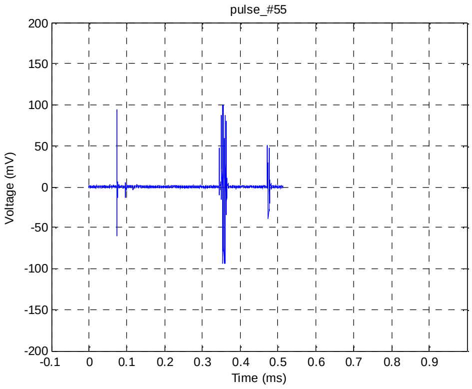

pulse_#50
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
Time (ms)

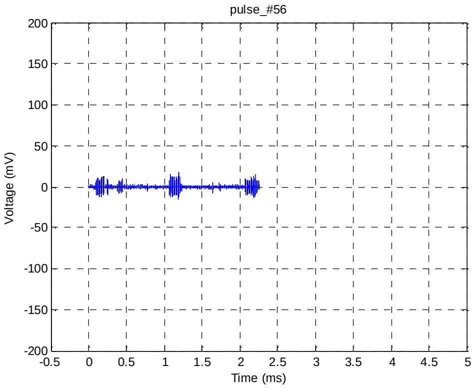

pulse_#51
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
Time (ms)

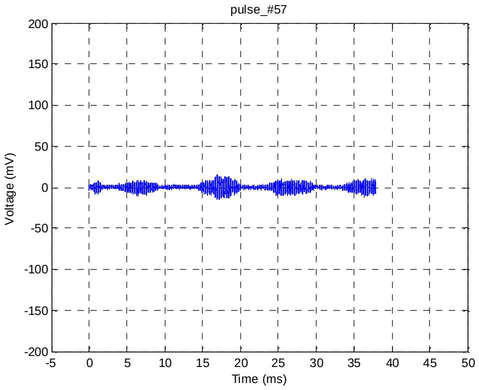

pulse_#52
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
Time (ms)

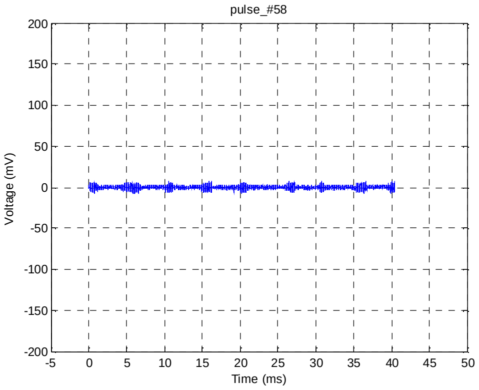

pulse_#53
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
Time (ms)

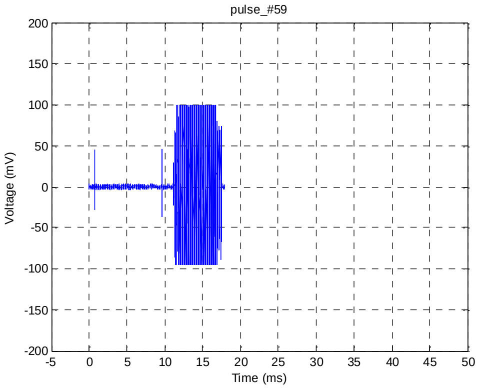

pulse_#54
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
Time (ms)

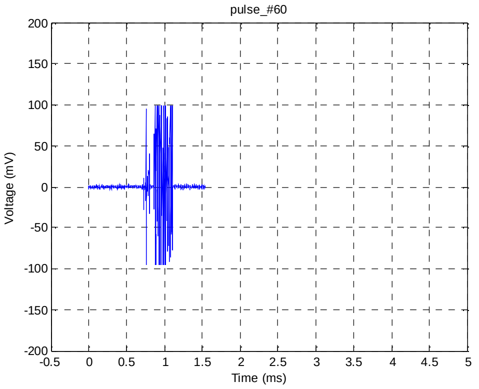

pulse_#55
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
Time (ms)

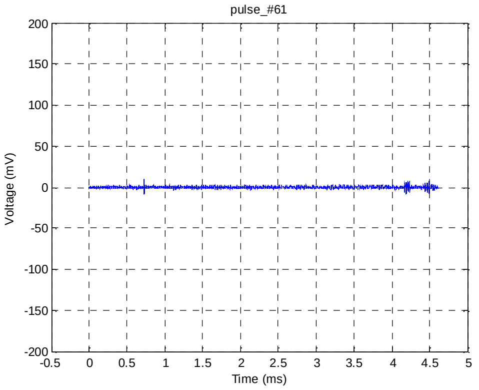

pulse_#56
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
Time (ms)

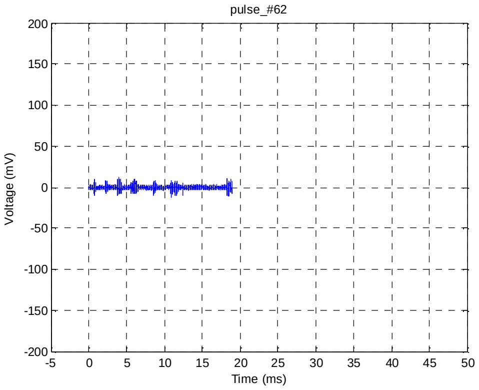

pulse_#57
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-5
0
5
10
15
20
25
30
35
40
45
50
Time (ms)

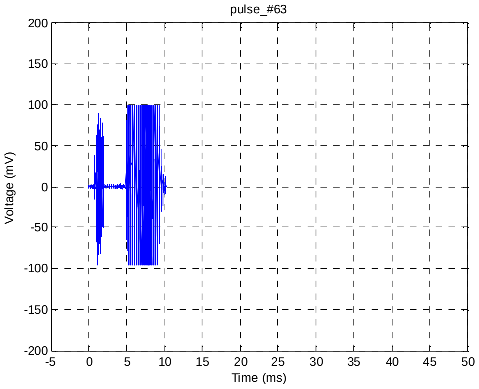

pulse_#58
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-5
0
5
10
15
20
25
30
35
40
45
50
Time (ms)

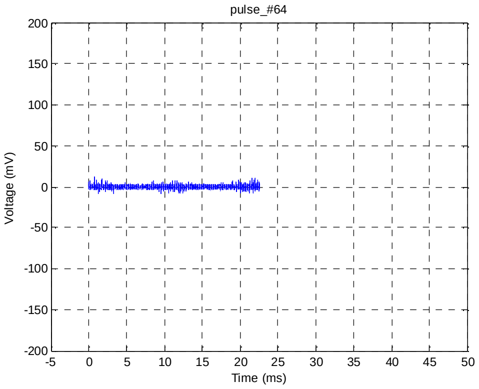

pulse_#59
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-5
0
5
10
15
20
25
30
35
40
45
50
Time (ms)

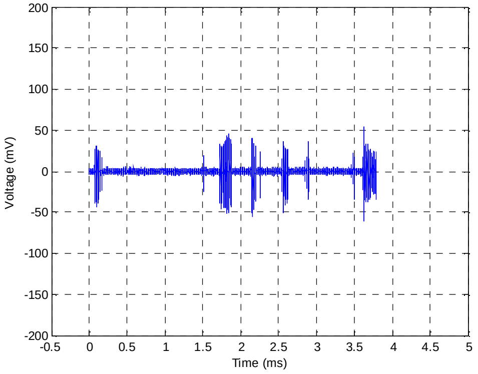

pulse_#60
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

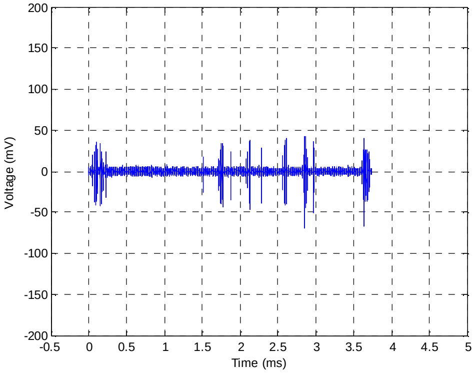

pulse_#61
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (ms)

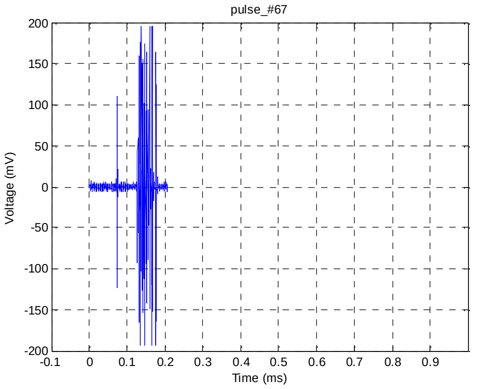

pulse_#62
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-5
0
5
10
15
20
25
30
35
40
45
50
Time (ms)

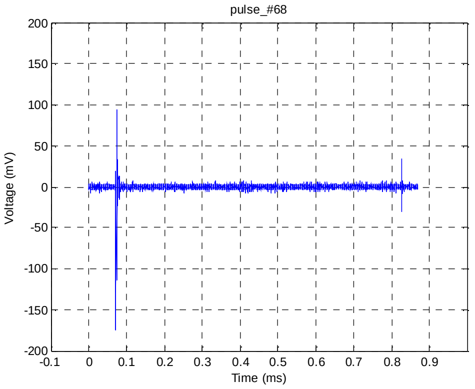

pulse_#63
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-5
0
5
10
15
20
25
30
35
40
45
50
Time (ms)

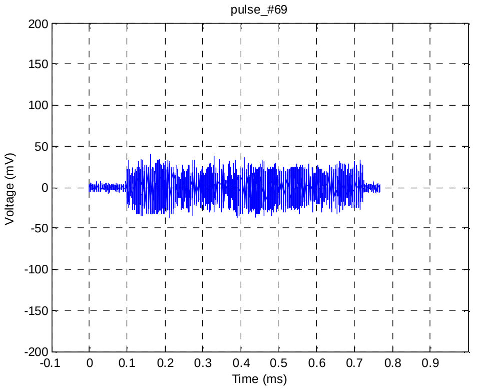

pulse_#64
Voltage (mV)
200
150
100
50
0
-50
-100
-150
-200
-5
0
5
10
15
20
25
30
35
40
45
50
Time (ms)

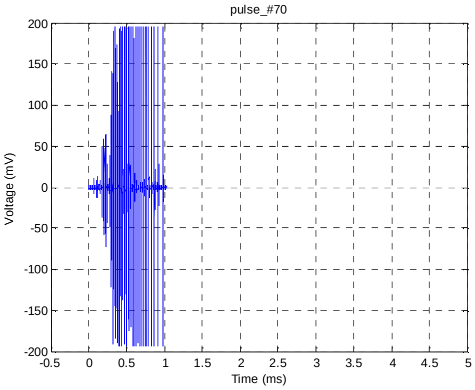

pulse_#65

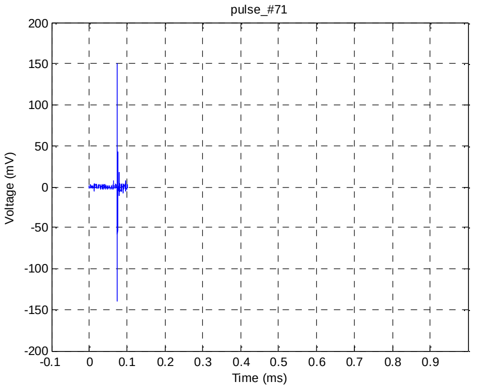

pulse_#66

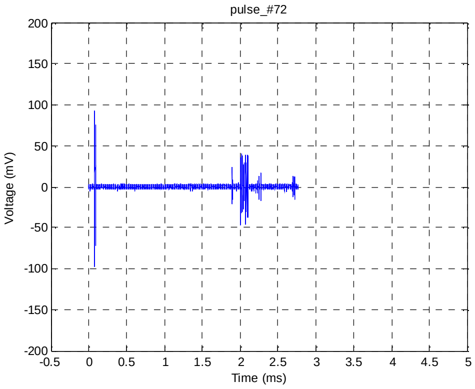

pulse_#67

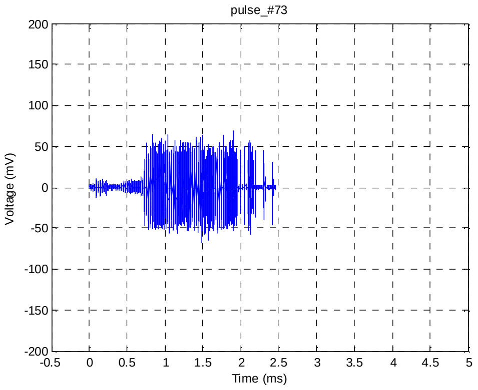

pulse_#68

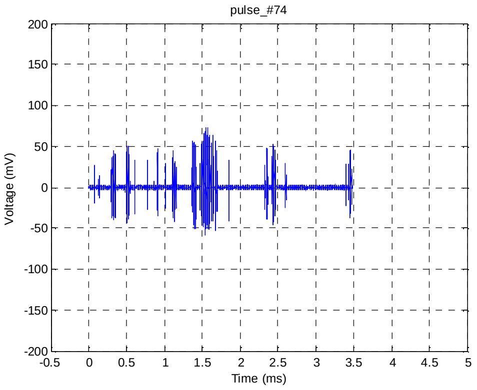

pulse_#69

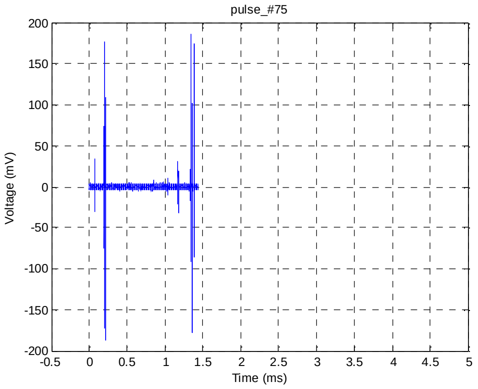

pulse_#70

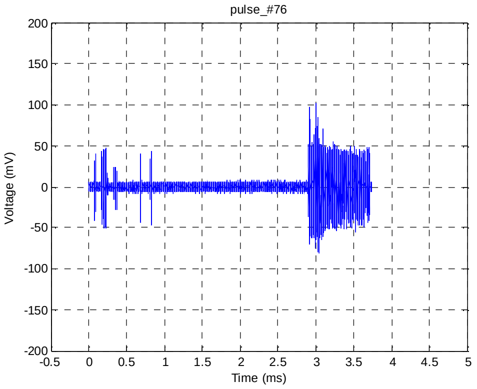

pulse_#71

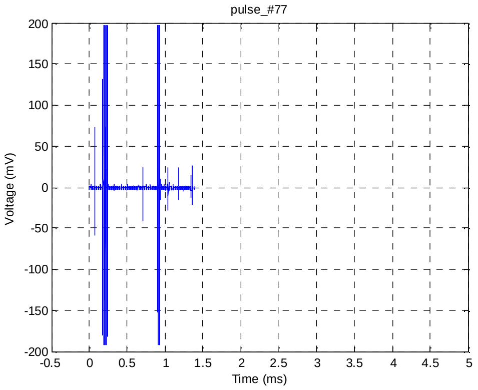

pulse_#72

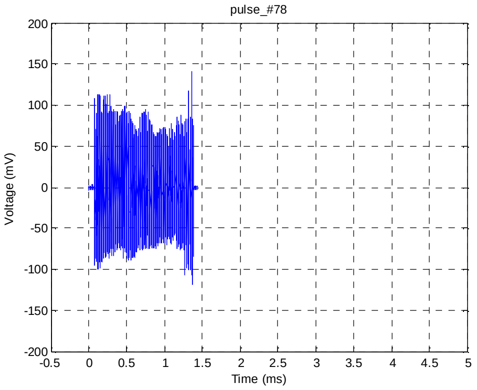

pulse_#73

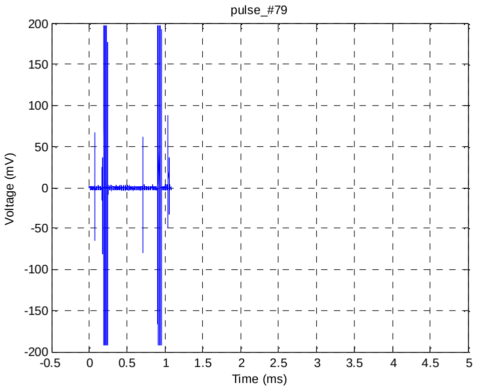

pulse_#74

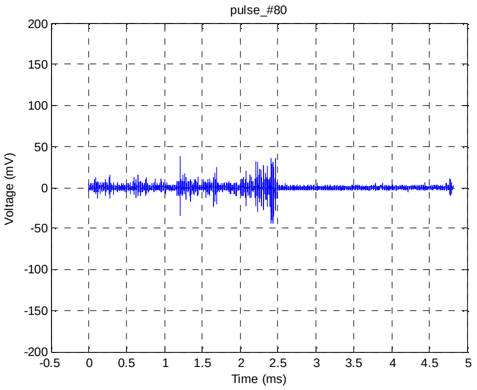

pulse_#75


pulse_#76


pulse_#77


pulse_#78


pulse_#79


pulse_#80